1. METHODOLOGY

This report is the second edition of *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste*. We made the following improvements to the first edition of the report:

- Incorporated new energy data and information on recycling loss rates from EPA's Office of Research and Development (ORD);

- Expanded analysis of the GHG benefits of composting, including results of CENTURY model runs;

- Developed emission factors for five new material types: magazines/third-class mail, phonebooks, textbooks, dimensional lumber, and medium-density fiberboard;

- Developed emission factors for two new categories of mixed materials: mixed plastics and mixed organics;

- Updated national recovery and generation rates to include 2000 data;

- Incorporated new energy data into calculations of utility offsets;

- Revised carbon coefficients and fuel use for national average electricity generation;

- Updated information on landfill gas recovery rates;

- Added a discussion of emerging issues in the area of climate change and waste management; and

- Provided a list of suggested proxy values for voluntary reporting of GHG emission reductions.

All of these changes and/or revisions are described in more detail throughout the body of the report.

Because this is the second edition, we have moved some of the background information from the body of the report to background documents, which are available in the docket in the Resource Conservation and Recovery Act (RCRA) Information Center. Background Document A provides data on life-cycle energy intensity and fuel mix, provided by Franklin Associates, Ltd. (FAL) (All other background documents, and this report, were written by ICF Consulting.) Background Document B provides a discussion of the review cycles leading up to the first and second editions of the report. Background Document C includes a discussion of how we screened materials for the first edition of the report.

The remainder of this chapter provides an overview of the methodology used to calculate the GHG emissions associated with various management strategies for MSW. The first section briefly describes the life-cycle framework used for the analysis. Next is a discussion of the materials included in the analysis. The final three sections present a description of key inputs and baselines, a summary of the life-cycle stages, and an explanation of how to estimate and compare net GHG emissions and sinks.

1.1 THE OVERALL FRAMEWORK: A STREAMLINED LIFE-CYCLE INVENTORY

Early in this analysis of the GHG benefits of specific waste management practices, it became clear that all waste management options provide opportunities for reducing GHG emissions, depending on individual circumstances. Although source reduction and recycling are often the most advantageous waste management practices from a GHG perspective, a material-specific comparison of all available waste management options would clarify where the greatest GHG benefits can be obtained for particular materials in MSW. A material-specific comparison can help policymakers identify the best options for GHG reductions.

This study determined that the best way to conduct such a comparative analysis is a streamlined application of a life-cycle assessment (LCA). A full LCA is an analytical framework for understanding the material inputs, energy inputs, and environmental releases associated with manufacturing, using, and disposing of a given material. A full LCA generally consists of four parts: (1) goal definition and scoping; (2) an inventory of the materials and energy used during all stages in the life of a product or process, and an inventory of environmental releases throughout the product life cycle; (3) an impact assessment that examines potential and actual human health effects related to the use of resources and environmental releases; and (4) an assessment of the change that is needed to bring about environmental improvements in the product or processes.

A full LCA is beyond the scope of this analysis. Rather, the streamlined LCA described in this report is limited to an inventory of the emissions and other environmental impacts related to global warming. This study did not assess human health impacts, necessary environmental improvements, and air, water, or environmental impacts that do not have a direct bearing on climate change.

1.2 MSW MATERIALS CONSIDERED IN THE STREAMLINED LIFE-CYCLE INVENTORY

Each material in MSW has different GHG impacts depending on how it is manufactured and disposed of. We began our research by performing a screening analysis of 37 of the most common materials and products found in MSW.[1] The materials included in screening analysis then were ranked by their potential for GHG reductions.[2] The first edition of the report included 12 materials: aluminum cans, steel cans,[3] glass, high-density polyethylene (HDPE) plastic blow-molded containers, low-density polyethylene (LDPE) plastic blow-molded containers, polyethylene terephthalate (PET) plastic blow-molded containers, corrugated cardboard, newspaper, office paper,[4] and three grades of mixed paper (broad, residential, and office). In addition to these materials, we examined the GHG implications of various management strategies for food discards, yard trimmings, mixed MSW, and mixed recyclables.

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[1] In addition to the materials and products covered in the first edition of the report, the screening analysis included the following materials and products: other paper materials (bags and sacks, other paper packaging, books, other paperboard packaging, wrapping papers, paper plates and cups, folding cartons, other nonpackaging paper, and tissue paper and towels), other plastic materials (plastic wraps, plastic bags and sacks, other plastic containers, and other plastic packing), other metal materials (aluminum foil/closures, other steel packaging), and other miscellaneous materials (miscellaneous durable goods, wood packaging, furniture and furnishings, carpet and rugs, and other miscellaneous packaging).

[2] For more information on the screening analysis used to identify materials for the first edition of the report, see Background Document C.

[3] Other steel materials also may be recycled, but this analysis was limited to steel cans from households.

[4] Office paper refers to the type of paper used in computer printers and photocopiers.

Comparison of EPA/ORD and EPA/OSW Emission Factors

Efforts to harmonize our previous life-cycle emission factors with the results of recent work by EPA's Office of Research and Development (ORD) began in October 2000. Noticing significant differences in our bottom line emission factors, we compared a range of assumptions, including energy consumption, fuel mix, loss rates, landfill oxidation rate, timing of landfill methane emissions, fraction of landfill gas collected, electricity mix, transportation distances, and carbon storage. Our comparison of energy intensities and fuel mixes included process and transportation energy for virgin and recycled production of each material type. Because the previous Office of Solid Waste (OSW) energy values were based on an average of Franklin Associates, Ltd. (FAL) and Tellus data, we compared the ORD values to the FAL data, Tellus data, and average of FAL and Tellus data.

This comparison revealed that the differences between the OSW and ORD emission factors are mostly attributable to the different assumptions about energy consumption (i.e., the sum of precombustion, process, and transportation energy), fuel mix, and loss rates. In general, we found that ORD's total energy values are lower than OSW's energy values for both virgin and recycled materials. Comparing fuel mix, we found the most significant differences occurring for electricity, coal, natural gas, and "other" fuel types comprising process energy. The fractions of diesel fuel, residual fuel, and natural gas exhibited the greatest disparities for transportation energy. Our comparison of loss rates, which are used to develop the recycling emission factors, showed significant variation for office paper, steel cans, and, to a lesser extent, newspaper.

In an effort to reconcile the remaining differences between ORD and OSW estimates of GHG emissions from the acquisition of raw materials and their manufacture into products, we identified additional methodological differences that could be affecting the recycling numbers. In particular, we found that ORD simulates closed-loop recycling for all materials, while OSW assumes open-loop recycling for office paper and corrugated cardboard. We also found that ORD's estimates do not include non-energy process emissions from perfluorocarbons (PFCs). To isolate any remaining differences between the two analyses, we substituted ORD energy intensities, fuel mixes, and loss rates into the OSW model.

Once we had identified and resolved all methodological differences between ORD and OSW estimates for raw materials acquisition and manufacturing, we selected the material types for which we could substitute ORD data for the existing OSW data: aluminum, glass, HDPE, LDPE, PET, corrugated cardboard, magazines/third-class mail, newspaper, office paper, phonebooks, and textbooks. For wood products, ORD did not develop emission factors, while for steel its data was not sufficiently disaggregated to replace the existing OSW data.

Most of the changes from the first edition of this report reflect additions of new or updated data. This second edition features an expanded list of material types, including magazines and third-class mail, phonebooks, textbooks, dimensional lumber, medium-density fiberboard, and several additional categories of mixed recycled materials (e.g. mixed plastics, mixed organics). This edition also incorporates updated data developed by ORD through its work on life-cycle management of MSW. ORD's data set on energy, fuel mix, and loss rates has been thoroughly reviewed by industry and other stakeholders, and is likely to be more up-to-date than some of the information in the first edition of this report. Thus, where a complete set of energy intensity and fuel mix data was available from ORD, that information was incorporated in this report. For other materials—steel cans and mixed paper (broad, residential, and office definitions)—we retained the original data set developed by FAL. This edition includes new data (also developed by FAL) on dimensional lumber and medium-density fiberboard. Exhibit 1-1 lists the materials that were analyzed for this report and the energy-related data sources underlying the estimates. All of the material types listed in Exhibit 1-1 are discussed in subsequent chapters and included in exhibits throughout the report, with the exception of three mixed waste categories. Mixed plastics, mixed recyclables, and mixed organics are included only in Chapter 8 because emission factors for these materials simply reflect the weighted average emissions of other material types.

Exhibit 1-1 Materials Analyzed and Energy-related Data Sources

Material	Energy Data Source	Material	Energy Data Source
Aluminum Cans	ORD	Medium-Density Fiberboard	FAL
Steel Cans	FAL	Food Discards	NA
Glass	ORD	Yard Trimmings	NA
Corrugated Cardboard	ORD	Mixed Paper – Broad Definition	FAL
Magazines/Third-class Mail	ORD	Mixed Paper – Residential Definition	FAL
Newspaper	ORD	Mixed Paper – Office Paper Definition	FAL
Office Paper	ORD	Mixed Plastics	Weighted Average
Phonebooks	ORD	Mixed Recyclables	Weighted Average
Textbooks	ORD	Mixed Organics	NA
Dimensional Lumber	FAL	Mixed MSW	NA

NA = Not applicable (data not energy-related)

1.3 KEY INPUTS AND BASELINES FOR THE STREAMLINED LIFE-CYCLE INVENTORY

Evaluating the GHG emissions of waste management requires analysis of three factors: (1) GHG emissions throughout the life cycle of the material (including the chosen disposal option); (2) the extent to which carbon sinks are affected by manufacturing and disposing of the material; and (3) the extent to which the management option recovers energy that can be used to replace electric utility energy, thus reducing utility GHG emissions. In addition, to provide a consistent basis for comparison, we made several choices in our GHG accounting framework in terms of timing and levels of production. Each of these factors warrants further discussion.

GHG Emissions Relevant to Waste: The most important GHGs for purposes of analyzing MSW management options are CO_2, CH_4, N_2O, and perfluorocarbons (PFCs). Of these, CO_2 is by far the most common GHG emitted in the United States. Most CO_2 emissions result from energy use, particularly fossil fuel combustion. A great deal of energy is consumed when a product is manufactured and then discarded. This energy is used in the following stages: (1) extracting and processing raw materials; (2) manufacturing products; (3) managing products at the end of their useful lives; and (4) transporting materials and products between each stage of their life cycles. This study estimated energy-related GHG emissions during all of these stages, except for transportation of products to consumers (because GHG emissions resulting from transportation to consumers will vary little among the options considered). Much of this report is devoted to explaining the methodology

> **Comparing GHGs**
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> Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are very different gases in terms of their heat-trapping potential. An international protocol has established CO_2 as the reference gas for measurement of heat-trapping potential (also known as global warming potential or GWP). By definition, the GWP of 1kilogram (kg) of CO_2 is 1.
>
> CH_4 has a GWP of 21, which means that 1 kg of methane has the same heat-trapping potential as 21 kg of CO_2.
>
> N_2O has a GWP of 310.
>
> PFCs are the most potent GHG included in this analysis; GWPs are 6,500 for CF_4 and 9,200 for C_2F_6.
>
> In this report, emissions of CO_2, CH_4, N_2O, and PFCs have been converted to their "carbon equivalents." Because CO_2 is 12/44 carbon by weight, 1 metric ton of CO_2 is equal to 12/44 or 0.27 metric tons of carbon equivalent (MTCE). The MTCE value for 1 metric ton of each of the other gases is determined by multiplying its GWP by a factor of 12/44. (All data provided here are from The Intergovernmental Panel on Climate Change (IPCC), *Climate Change 1995: The Science of Climate Change*, 1996, p. 121.)

point in the life cycle. In addition, the energy consumed during use would be about the same whether the product is made from virgin or recycled inputs.

CH_4, a more potent GHG, is produced when organic waste decomposes in an oxygen-free (anaerobic) environment, such as a landfill. CH_4 from landfills is the largest source of CH_4 in the United States;[5] these emissions are addressed in Chapter 7. CH_4 is also emitted when natural gas is released to the atmosphere during production of coal or oil, production or use of natural gas, and agricultural activities.

N_2O results from the use of commercial and organic fertilizers and fossil fuel combustion, as well as other sources. This analysis estimated N_2O emissions from waste combustion.

Perfluorocarbons (CF_4 and C_2F_6) are emitted during the reduction of alumina to aluminum in the primary smelting process. The source of fluorine for CF_4 and C_2F_6 is the molten cryolite (Na_3AlF_6) where the reduction of alumina occurs. Perfluorocarbons are formed when the fluorine in cryolite reacts with the carbon in the anode (a carbon mass of paste, coke briquettes, or prebaked carbon blocks) and in the carbon lining that serves as the cathode. Although the quantities of perfluorocarbons emitted are small, these gases are significant because of their high global warming potential.

Carbon Stocks, Carbon Storage, and Carbon Sequestration: This analysis includes carbon storage to the extent that it is due to waste management practices. For example, landfilled organic materials result in landfill carbon storage, as carbon is moved from a product pool (e.g., furniture) to the landfill pool. The same is true for composted organics that lead to carbon storage in soil.

Carbon sequestration differs from carbon storage because it represents a transfer of carbon from the atmosphere to a carbon pool. For example, trees in a forest undergo photosynthesis, converting CO_2 in the atmosphere to carbon in biomass. In this analysis, we consider the impact of waste management on forest carbon sequestration.

The baseline against which changes in carbon stocks are measured is a projection by the U.S. Forest Service of forest growth, mortality, harvests, and other removals under anticipated market conditions for forest products. One of the assumptions for the projections is that U.S. forests will be harvested on a sustainable basis (i.e., trees will be grown at a rate at least equal to the rate at which they are cut).[6] Thus, the baseline assumes that harvesting trees at current levels results in no diminution of the forest carbon stock and no additional CO_2 in the atmosphere. On the other hand, forest carbon sequestration *increases* as a result of source reduction or recycling of paper products because both source reduction and recycling cause annual tree harvests to drop below otherwise anticipated levels (resulting in additional accumulation of carbon in forests). Consequently, source reduction and recycling "get credit" for increasing the forest carbon stock, whereas other waste management options (combustion and landfilling) do not.

Although source reduction and recycling are associated with forest carbon sequestration, composting—in particular, application of compost to degraded soils—enhances soil carbon storage. Four mechanisms of increased carbon storage are hypothesized in Chapter 5; a modeling approach is used to estimate the magnitude of carbon storage associated with three of these mechanisms.

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[5] U.S. EPA. 2001.*Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999*. U.S. Environmental Protection Agency, Office of Policy, Planning and Evaluation, Washington, DC. EPA-236-R-01-001.

[6] Assuming a sustainable harvest in the United States is reasonable because from 1952 to 1997 U.S. forest carbon stocks steadily increased. In the early part of this period, the increases were mostly due to reversion of agricultural land to forest land. More recently, improved forest management practices and the regeneration of previously cleared forest areas have resulted in a net annual uptake (sequestration) of carbon. The steady increase in forest carbon stocks implies sustainable harvests, and it is reasonable to assume that the trend of sustainable harvests will continue.

Finally, landfills are another means by which carbon is removed from the atmosphere. Landfill carbon stocks increase over time because much of the organic matter placed in landfills does not decompose, especially if the landfill is located in an arid area. However, not all carbon in landfills is counted in determining the extent to which landfills are carbon stocks. For example, the analysis does not count plastic in landfills toward carbon storage. Plastic in a landfill represents simply a transfer from one carbon stock (the oil field containing the petroleum or natural gas from which the plastic was made) to another carbon stock (the landfill); thus, no change has occurred in the overall amount of carbon stored. On the other hand, the portion of organic matter (such as yard trimmings) that does not decompose in a landfill represents an addition to a carbon stock, because it would have largely decomposed into CO_2 if left to deteriorate on the ground.

Although changes in fossil fuel carbon stocks (i.e., reductions in oil field stores that result from the extraction and burning of oil resources) are not measured *directly* in this analysis, the reduction in fossil fuel carbon stocks is indirectly captured by counting the CO_2 emissions from fossil fuel combustion in calculating GHG emissions.

Avoided Electric Utility GHG Emissions Related to Waste: Waste that is used to generate electricity (either through waste combustion or recovery of CH_4 from landfills) displaces fossil fuels that utilities would otherwise use to produce electricity. Fossil fuel combustion is the single largest source of GHG emissions in the United States. When waste is substituted for fossil fuel to generate electricity, the GHG emissions from burning the waste are offset by the avoided electric utility GHG emissions.

Baseline Year: The baseline year selected for most parts of the analysis is the most recent year for which data are available. However, for the system efficiency and ferrous recovery rate at waste combustors, this study uses values previously projected for the year 2000. For paper recycling, annual projections through 2010 were used to develop an average forest carbon storage value for the period from 1996 through 2010.[7] The compost analysis relied on model simulations of compost application, beginning in 1996 and ending in 2005. The carbon storage estimates resulting from these model runs correspond to model outputs in 2010 in order to maintain consistency with forest carbon storage estimates. We developed "future"[8] scenarios for paper recycling, composting, and carbon storage analyses because some of the underlying factors that affect GHG emissions are changing rapidly, and this study seeks to define relationships (e.g., between tonnage of waste landfilled and CH_4 emissions) that represent an average over the next several years.

- Although the existing U.S. municipal waste combustors include a few small facilities that do not recover energy, the study assumes that those facilities will be closed in the near future. Thus, the report assumes that all combustors recover energy. The study used an estimate provided by the combustion industry for anticipated levels of ferrous recovery.

- For paper recycling, earlier analyses indicated that the marginal impact of increased paper recycling on forest carbon sequestration changes over time. The impact also differs depending on the initial paper recycling rate and how that rate changes over time. To estimate the impact of increased paper recycling on forest carbon sequestration, the study needed to account for these influences. First, we used the American Forest and Paper Association's baseline projection that paper recycling rates will continue to increase from about 35 percent

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[7] The models we used simulated carbon sequestration through 2040, but we selected a value based on average conditions through 2010.

[8] In the case of system efficiency and ferrous recovery at waste combustors, the year 2000 represented a future value when the first edition of this report was published. This edition of the report does not reflect these updated values because more recent data are not available.

in 1994 to 50 percent by 2000.[9] The trajectory for a baseline scenario for paper recycling passes through 50 percent in 2000, with continued modest increases in the following years. Because of the need to estimate the effect of efforts (e.g., by EPA) to enhance recycling beyond the baseline projected rate, we developed a plausible scenario for enhanced paper recycling rates and then compared the projected forest carbon sequestration under the baseline and increased recycling scenarios.[10] (This approach is fully described in Chapter 3.)

- The baseline for our landfill recovery scenario is based on estimated recovery rates and percentages of waste disposed in landfills with no recovery, landfills with flaring, and landfills with landfill-gas-to-energy projects for the year 2000. According to our estimates, 49 percent of all landfill CH_4 was generated at landfills with recovery systems, and the remaining 51 percent was generated at landfills without landfill gas (LFG) recovery.[11] Of the 49 percent of all CH_4 generated at landfills with LFG recovery, 49 percent (or 24 percent of all CH_4) was generated at landfills that use LFG to generate electricity, and 51 percent (or 25 percent of all CH_4) at landfills that flare LFG.[12,13]

1.4 SUMMARY OF THE LIFE-CYCLE STAGES

Exhibit 1-2 shows the GHG sources and carbon sinks associated with the manufacture of various materials and the post-consumer management of these materials as wastes. As shown in the exhibit, GHGs are emitted from (1) the pre-consumer stages of raw materials acquisition and manufacturing, and (2) the post-consumer stage of waste management. No GHG emissions are attributed to the consumer's use of any product.

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[9] Actual paper recovery in 2000 (taken from EPA's *Municipal Solid Waste in the United States: 2000 Facts and Figures*) averaged about 53%, confirming that 50 percent is a reasonable estimate for 2000.

[10] Note that this estimate is necessary for analyzing the scenarios; however, it does not represent a plan of action by EPA.

[11] Based on data on (1) year 2000 MSW landfill methane generation of 72.7 million MTCE (from draft *U.S. Climate Action Report – 2001*), (2) year 2000 landfill methane recovery of 26.7 million MTCE (also from draft *U.S. Climate Action Report – 2001*), and (3) estimated landfill methane recovery efficiency of 75 percent (from *U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions*).

[12] Draft *U.S. Climate Action Report – 2001*.

[13] The assumption that 49 percent of landfills recovering methane will use it to generate electricity is subject to change over time based upon changes in the cost of recovery, and the potential payback. Additionally, new technologies may arise that use recovered methane for purposes other than generating electricity.

Exhibit 1-2 Greenhouse Gas Sources and Sinks Associated with the Material Life Cycle
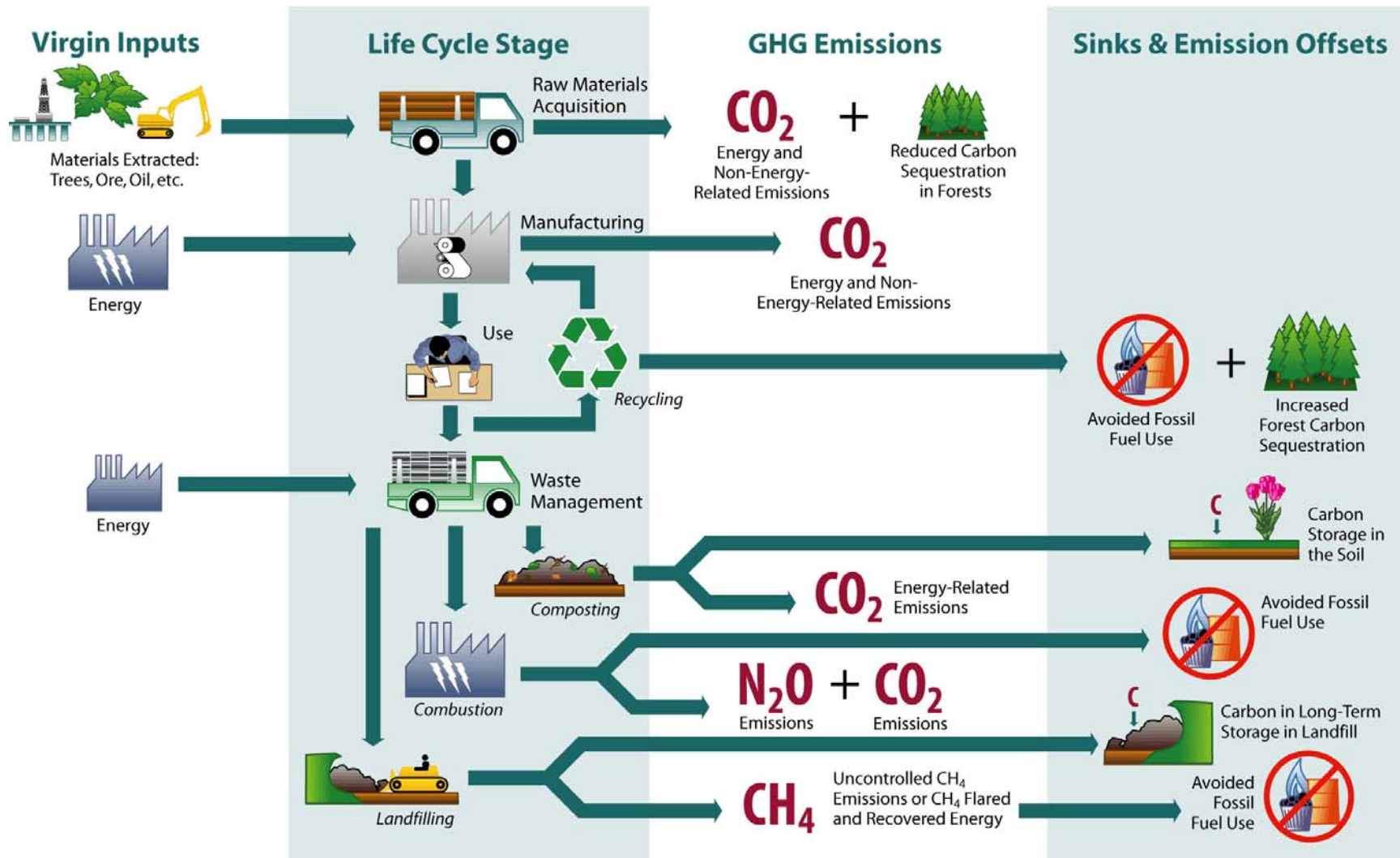
The remainder of this chapter describes how this study analyzed each of the upstream (raw materials acquisition, manufacturing, and forest carbon sequestration) and downstream (source reduction, recycling, composting, combustion, and landfilling) stages in the life cycle. The following sections explain stages of the life cycle and the corresponding emission factor components presented in Exhibit 1-3, and outline the GHG emissions and carbon sinks at each stage of the product life cycle. These GHG emissions and carbon sinks are described in detail and quantified for each material in Chapters 2 through 7.

Exhibit 1-3 Components of Net Emissions for Various MSW Management Strategies

MSW Management Strategy	GHG Sources and Sinks		
	Process and Transportation GHGs from Raw Materials Acquisition and Manufacturing	Forest Carbon Sequestration or Soil Carbon Storage	Waste Management GHGs
Source Reduction	Decrease in GHG emissions, relative to the baseline of manufacturing	Increase in forest carbon sequestration	No emissions/sinks
Recycling	Decrease in GHG emissions due to lower energy requirements (compared to manufacture from virgin inputs) and avoided process non-energy GHGs	Increase in forest carbon sequestration	Process and transportation emissions are counted in the manufacturing stage
Composting	No emissions/sinks*	Increase in soil carbon storage	Compost machinery emissions and transportation emissions
Combustion	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	No change	Nonbiogenic CO_2, N_2O emissions, avoided utility emissions, and transportation emissions
Landfilling	Baseline process and transportation emissions due to manufacture from the current mix of virgin and recycled inputs	No change	CH_4 emissions, long-term carbon storage, avoided utility emissions, and transportation emissions

* No manufacturing transportation GHG emissions are considered for composting of food discards and yard trimmings because these materials are not considered to be manufactured.

1.4.1   GHG Emissions and Carbon Sinks Associated with Raw Materials Acquisition and Manufacturing

The top left of Exhibit 1-2 shows inputs for *raw materials acquisition*. These virgin inputs are used to make various materials, including ore for manufacturing metal products, trees for making paper products, and petroleum or natural gas for producing plastic products. Fuel energy also is used to obtain or extract these material inputs.

The inputs used in *manufacturing* are (1) energy and (2) either virgin raw materials or recycled materials. In the exhibit these inputs are identified with arrows that point to the icon labeled "Manufacturing."

For source reduction, the "baseline" GHG emissions from raw materials acquisition and manufacturing are avoided. This analysis thus estimates, for source reduction, the GHG *reductions* (relative to a baseline of initial manufacture) at the raw materials acquisition and manufacturing stages. Source reduction is assumed to entail more efficient use of a given material. Examples are lightweighting (reducing the quantity of raw material in a product), double-sided photocopying, and extension of a product's useful life. No other material substitutions are assumed for source reduction; therefore, this report does not analyze any corresponding increases in production and disposal of other materials (which could result in GHG emissions).[14]

The GHG emissions associated with raw materials acquisition and manufacturing are (1) GHG emissions from energy used during the acquisition and manufacturing processes, (2) GHG emissions from energy used to transport materials,[15] and (3) non-energy GHG emissions resulting from manufacturing processes (for aluminum, steel, plastics, office paper, and medium-density fiberboard). Each type of emission is described below. Changes in carbon sequestration in forests also are associated with raw materials acquisition for paper products.

Process Energy GHG Emissions: Process energy GHG emissions consist primarily of CO_2 emissions from the combustion of fuels used in raw materials acquisition and manufacturing. CO_2 emissions from combustion of biomass are not counted as GHG emissions. (See "CO_2 Emissions from Biogenic Sources" on page 12.)

The majority of process energy CO_2 emissions are from combustion of fuels used directly, e.g., to operate ore mining equipment or to fuel a blast furnace. Fuel also is needed to extract the oil or mine the coal that is ultimately used to produce energy and transport these fuels to the place where they are used. Thus CO_2 emissions from this "pre-combustion energy" are counted in this category as well. When electricity generated by combustion of fossil fuels is used in manufacturing, the CO_2 emissions from the fossil fuels also are counted.

To estimate process energy GHG emissions, the study first obtained estimates of both the total amount of process energy used per ton of product (measured in British thermal units or Btu's), and the fuel mix (e.g., diesel oil, natural gas, fuel oil, etc.). Next, emissions factors for each type of fuel were used to convert the amount of each type of fuel used to GHG emissions. As noted earlier, making a material from recycled inputs generally requires less process energy (and uses a different fuel mix) than making the material from virgin inputs.

Details of the methodology for estimating process energy GHG emissions are provided in Chapter 2.

Transportation Energy GHG Emissions: Transportation energy GHG emissions consist of CO_2 emissions from the combustion of fuels used to transport raw materials and intermediate products to the final manufacturing or fabrication facility. The estimates of transportation energy emissions are based on: (1) the amounts of raw material inputs and intermediate products used in manufacturing 1 ton of each material; (2) the average distance that each raw material input or intermediate product is transported; and (3) the transportation modes and fuels used. For the amounts of fuel used, the study used data on the average fuel consumption per ton-mile for each mode of transportation.[16] Then an emission factor for

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[14] Although material substitution is not quantitatively addressed in the report, it is discussed from a methodological standpoint in Chapter 2 and also is discussed briefly in Chapter 4, Section 4.3.

[15] For some materials (plastics, magazines/third-class mail, office paper, phonebooks, and textbooks), the transportation data we received were included in the process energy data. For these materials, we report *total* GHG emissions associated with process and transportation in the "process energy" estimate.

[16] These data are found in Background Document A.

each type of fuel was used to convert the amount of each type of fuel consumed to the GHG emissions produced.

More detail on the methodology to estimate transportation energy GHG emissions is provided in Chapter 2.

Process Non-Energy GHG Emissions: Some GHG emissions occur directly in the manufacture of certain materials and are not associated with energy consumption. In this analysis, these emissions are referred to as *process non-energy emissions*. For example, the production of steel or aluminum requires lime (calcium oxide, or CaO), which is produced from limestone (calcium carbonate, or $CaCO_3$), and the manufacture of lime results in CO_2 emissions. Other process non-energy GHG emissions are associated with the manufacture of plastics, office paper, and medium-density fiberboard. In some cases, process non-energy GHG emissions are associated only with production using virgin inputs; in other cases, these emissions result when either virgin or recycled inputs are used. These emissions are described in Chapter 2.

Carbon Sinks: The only carbon sink during the stages of raw materials acquisition and manufacturing is the additional carbon sequestration in trees associated with source reduction or recycling of paper products. The methodology for estimating forest carbon sequestration is described in Chapter 3.

1.4.2   GHG Emissions and Carbon Sinks Associated with Waste Management

As shown in Exhibit 1-3, there are up to five post-consumer waste management options, depending on the material: recycling, composting, combustion, and landfilling. This section describes the GHG emissions and carbon sinks associated with these five options.

Source Reduction: In this analysis, source reduction is measured by the amount of material that would otherwise be produced but is not generated due to a program promoting source reduction. Thus, with source reduction there are no emissions from MSW management.

Recycling: When a material is recycled, it is used in place of virgin inputs in the manufacturing process. The avoided GHG emissions from remanufacture using recycled inputs is calculated as the difference between (1) the GHG emissions from manufacturing a material from 100 percent recycled inputs, and (2) the GHG emissions from manufacturing an equivalent amount of the material (accounting for loss rates) from 100 percent virgin inputs (including the process of collecting and transporting the recyclables). No GHG emissions occur at the MSW management stage because the recycled material is diverted from waste management facilities.[17] (If the product made from the recycled material is later composted, combusted, or landfilled, the GHG emissions at that point would be attributed to the product that was made from the recycled material.) Chapter 4 details GHG emissions from recycling.

All of the materials considered in this analysis are modeled as being recycled in a "closed loop" (e.g., newspaper is recycled into new newspaper). However, a variety of paper types are recycled under the general heading of "mixed paper." Mixed paper can be remanufactured, via an open loop, into boxboard or paper towels. Other materials are recycled in open-loop processes, but due to limited resources, this study could not analyze all open-loop processes.[18]

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[17] We do not include GHG emissions from managing residues (e.g., wastewater treatment sludges) from the manufacturing process for either virgin or recycled inputs.

[18] For example, not all steel cans are recycled into more steel cans; not all aluminum cans are recycled into more aluminum cans.

CO$_2$ Emissions from Biogenic Sources

The United States and all other parties to the U.N. Framework Convention on Climate Change (UNFCCC) agreed to develop inventories of GHGs for purposes of (1) developing mitigation strategies and (2) monitoring the progress of those strategies. The Intergovernmental Panel on Climate Change (IPCC) developed a set of inventory methods to be used as the international standard. (IPCC 1997. *IPCC Guidelines for National Greenhouse Gas Inventories*, three volumes.) The methodologies used in this report to evaluate emissions and sinks of GHGs are consistent with the IPCC guidance.

One of the elements of the IPCC guidance that deserves special mention is the approach used to address CO$_2$ emissions from biogenic sources. For many countries, the treatment of CO$_2$ releases from biogenic sources is most important when addressing releases from energy derived from biomass (e.g., burning wood), but this element is also important when evaluating waste management emissions (for example, the decomposition or combustion of grass clippings or paper). The carbon in paper and grass trimmings was originally removed from the atmosphere by photosynthesis, and under natural conditions, it would cycle back to the atmosphere eventually as CO$_2$ due to degradation processes. The quantity of carbon that these natural processes cycle through the Earth's atmosphere, waters, soils, and biota is much greater than the quantity added by anthropogenic GHG sources. But the focus of the UNFCCC is on anthropogenic emissions—those resulting from human activities and subject to human control. Those emissions have the potential to alter the climate by disrupting the natural balances in carbon's biogeochemical cycle and altering the atmosphere's heat-trapping ability. For processes with CO$_2$ emissions, if the emissions are from biogenic materials and the materials are grown on a sustainable basis, then those emissions are considered simply to close the loop in the natural carbon cycle. They return to the atmosphere CO$_2$ that was originally removed by photosynthesis. In this case, the CO$_2$ emissions are *not* counted. (For purposes of this analysis, biogenic materials are paper, yard trimmings, and food discards.) On the other hand, CO$_2$ emissions from burning fossil fuels *are* counted because these emissions would not enter the cycle were it not for human activity. Likewise, CH$_4$ emissions from landfills *are* counted. Even though the source of carbon is primarily biogenic, CH$_4$ would not be emitted were it not for the human activity of landfilling the waste, which creates anaerobic conditions conducive to CH$_4$ formation. Note that this approach does not distinguish between the timing of CO$_2$ emissions, provided that they occur in a reasonably short time scale relative to the speed of the processes that affect global climate change. In other words, as long as the biogenic carbon would eventually be released as CO$_2$, it does not matter whether it is released virtually instantaneously (e.g., from combustion) or over a period of a few decades (e.g., decomposition on the forest floor).

Composting: When organic materials are composted, the anaerobic decomposition of materials produces CH$_4$. Similarly, the collection and transportation of organics produces non-biogenic emissions. During the composting process and after the compost is added to the soil, the decomposition of plants produces biogenic CO$_2$ emissions. Carbon compounds that do not decompose, however, result in long-term carbon storage. All of the materials that may be composted (e.g., leaves, brush, grass, food waste, newspaper) originally are produced by trees or other plants. As described in the above in "CO$_2$ Emissions from Biogenic Sources," the biogenic CO$_2$ emitted from these materials during composting is not counted in GHG emissions. However, composting does result in increased soil carbon storage due to increased production of humic material (natural organic polymers, which degrade at a slow rate) and several other factors, which are described in Chapter 5.

Although composting may result in some production of CH$_4$ (due to anaerobic decomposition in the center of the compost pile), compost researchers believe that the CH$_4$ is almost always oxidized to CO$_2$ before it escapes from the compost pile.

Because the CO$_2$ emissions from composting are biogenic—generally producing no CH$_4$ emissions—the only GHG emissions from composting result from transportation of compostable materials to composting facilities and mechanical turning of the compost piles. GHG emissions associated with compost application are discussed in Chapter 5.

Combustion: When waste is combusted, two GHGs are emitted: CO_2 and N_2O. Non-biogenic CO_2 emitted during combustion (i.e., CO_2 from plastics) is counted toward the GHG emissions associated with combustion, but biogenic CO_2 is not. Because most waste combustors produce electricity that substitutes for utility-generated electricity, the net GHG emissions are calculated by subtracting the utility GHG emissions avoided from the gross GHG emissions. GHG emissions from combustion are described in Chapter 6.

Landfilling: When organic matter is landfilled, some of this matter decomposes anaerobically and releases CH_4, a GHG. Some of the organic matter never decomposes at all; instead, it becomes stored carbon. (Landfilling of metals and plastics does not result in either CH_4 emissions or carbon storage.)

At some landfills, virtually all of the CH_4 produced is released to the atmosphere. At others, CH_4 is captured for flaring or combustion with energy recovery (i.e., electricity production). Most of the captured CH_4 is converted to CO_2, but that CO_2 is not counted in this study as a GHG because it is biogenic. With combustion of CH_4 for energy recovery, credit is given for the electric utility GHG emissions avoided. Regardless of the fate of the CH_4, credit is given for the landfill carbon storage associated with landfilling of some organic materials. GHG emissions and carbon sinks from landfilling are described in Chapter 7.

1.5   ESTIMATING AND COMPARING NET GHG EMISSIONS

To calculate the net GHG implications of a waste management strategy for a given material, a baseline and alternative scenarios must be established. For example, a baseline scenario in which 10 tons of office paper are manufactured, used, and landfilled could be compared with an alternative scenario in which 10 tons are manufactured, used, and recycled. For each scenario, net GHG emissions are estimated based on (1) the GHG emissions associated with that material, and (2) any increases in carbon stocks and/or displaced fossil fuel combustion that offset those emissions. The formula for net GHG emissions is as follows:

Net GHG emissions = Gross GHG emissions - (Increase in carbon stocks + Avoided utility GHG emissions)

Comparing net GHG emissions for the two scenarios enables the lowest net GHG emissions to be identified. For example, when a material is source reduced (i.e., some or all of it is not produced), GHG emissions throughout the life cycle are avoided. In addition, when paper products are source reduced, additional carbon may be sequestered in forests.

Similarly, when a material is recycled, the GHG emissions from making an equivalent amount of material from virgin inputs are reduced. In most cases, recycling reduces GHG emissions because manufacturing a product from recycled inputs requires less fossil energy than making the product from virgin inputs and thus reduces energy-related GHG emissions.

If a waste is not source reduced or recycled, it may be either composted (if it is organic matter), combusted, or landfilled. In any of these cases, GHG emissions are produced during acquisition and manufacture. These GHG emissions may be augmented by CH_4 emissions from landfills (which themselves may be offset to some degree by energy recovery at landfills or landfill carbon storage). If the wastes are combusted, there may be an offset for avoided utility emissions.

In calculating emissions for the life-cycle scenarios, we can use the following two reference points:

- In a "raw material extraction" approach (i.e., cradle-to-grave perspective), raw material acquisition can be used as the "zero point" for emissions, with all emissions being added (and sinks deducted) from that point on through the life cycle.

- In a "waste-generation" approach (solid waste manager's perspective), accounting for GHG emissions can start at the point of waste generation. All subsequent emissions and sinks from waste management practices then are accounted for. Changes in emissions and sinks from raw material acquisition and manufacturing processes are captured to the extent that certain waste management practices (i.e., source reduction and recycling) affect these processes.

Because it is the difference in emissions between the baseline and alternate scenarios that is meaningful, using either of these reference points yields the same results. The March 1997 draft working paper used the cradle-to-grave method to display GHG emissions because it is most consistent with standard accounting techniques for life-cycle inventories. Several reviewers pointed out that solid waste decision-makers tend to view raw materials acquisition and manufacturing as beyond their control and suggested that a waste generation GHG accounting approach would provide increased clarity for evaluating waste management options. Thus, both editions of this report use the waste generation approach and define the "standard" raw material acquisition and manufacturing step for each material as consisting of average GHG emissions based on the current mix of virgin and recycled inputs.[19]

Exhibit 1-3 indicates how GHG sources and sinks have been counted for each MSW management strategy in order to estimate net GHG emissions using the post-consumer reference point. For example, the top row of the exhibit shows that source reduction (1) reduces GHG emissions from raw materials acquisition and manufacturing, (2) results in an increase in forest carbon sequestration, and (3) does not result in GHG emissions from waste management. The sum of emissions (and sinks) across all steps in the life cycle represents net emissions. Section 8.2, "Applying Emission Factors," describes how waste managers and companies have used these emission factors to estimate GHG emissions and potential GHG emission reductions associated with integrated waste management. In addition, EPA used these emission factors to develop the Waste Reduction Model (WARM). WARM enables users to analyze the GHG savings associated with changing their waste management practices. WARM is available on EPA's Web site at <http://www.epa.gov/globalwarming/actions/waste/warm.htm>.

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[19] Changes in the mix of production (i.e., higher proportions of either virgin or recycled inputs) result in incremental emissions (or reductions) with respect to this reference point.